YIP: Generic Environment Models (GEMs) for Agile Marine Autonomy

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LONG-TERM GOALS

This project builds a roadmap to achieve agile marine autonomy that endows unmanned marine systems with ability to take fast responses to environmental changes. Agile marine autonomy may help unmanned systems to out maneuver opponents in future naval battles.

OBJECTIVES

The proposal will overcome the demand for significant amount of computing resources and complex software packages from existing ocean modeling methods.The technical objectives include the following:

1. Establish the methodology of constructing generic environment models (GEMs). A GEM does not rely on a specific region or a specific ocean process. It can have higher resolution in both space and time and can be computed much faster than classical ocean models. In combination with existing ocean models, GEMs enable navigation of mobile agents in the marine environment in real time.
2. Develop control and navigation algorithms that benefit from the GEMs. GEM provides fast information to unmanned systems whose motion also affects the quality of GEMs. Through a new theory called Controlled Lagrangian Particle Tracking (CLPT), we develop methods to refine control and navigation algorithms due to GEMs.
3. Provide multi-disciplinary training to graduate and undergraduate students who will be the future task-force in marine technology.

GEMs for agile marine autonomy reflect a tight integration of research in robotics/control with research in physical oceanography. On one hand, it may significantly extend the capabilities of existing ocean modeling theory to better serve operations of autonomous agents. On the other hand, it may results in novel map-making methods and navigation methods in four-dimensional marine processes that have not been achieved in the field of robotics. Therefore, the proposed research program may create new opportunities to advance both oceanography and robotics/control engineering research.

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APPROACH

The work is performed by PI Fumin Zhang and four graduate students in Georgia Tech: Paul Varnell (Fall 2010), Chuanfeng Wang (Fall 2010), Dongsik Chang (Fall 2009), Klementyna Szwaykowska (Fall 2007). In addition, three undergraduate students are hired on an hourly base to develop experimental marine robots. The PI is leading the team. Paul Varnell focuses on the control system and software system of the Yellowfin AUV developed by the Georgia Tech Research Institute (GTRI). Chuanfeng Wang focuses on the environmental modeling and map-making algorithms with implemenation on the YSI Ecomapper. Dongsik Chang focuses on the automation middleware systems and control of underwater gliders. Klementyna Szwaykowska focuses on the CLPT theory and path planning alogrithms using the Generic Environment Models. The approach and methodologies employed, corresponding to the above objectives, are as follows:

1. A novel methodology to construct the generic environment models (GEMs) will be established. The structure of the GEM will be determined through existing ocean models by parsing output data from the ocean models. A set of model updating algorithms will be developed to assimilate data collected by unmanned marine systems. The time required to compute different GEMs will be analyzed and compared.
2. The fundamental theoretical principles governing the interactions between the GEMs and unmanned systems will be discovered. These principles are formulated as the theory of controlled Lagrangian particle tracking (CLPT). In-depth analysis will be performed about the discrepancy between the trajectories of unmanned marine systems in the ocean and in predictions generated by using the GEMs.
3. Strategies to achieve agile marine autonomy with GEMs will be developed. PI’s work in automation middleware will be applied to implement GEMs. Method of controller refinement will be developed to extend PI’s work in bio-inspired autonomy to incorporate GEMs. Research will be performed to integrate GEMs with refined control and navigation algorithms to enable fast response to the environment.
4. Low cost and lab scale experiments will be carried out to validate and inspire the theoretical work. Methods and algorithms will be first tested on ground mobile robots in a lab. YSI Ecomapper and student developed marine robots will be used to perform experiments in a small lake. PI’s existing collaborations with the industry and Naval Research Labs will be leveraged to transfer the research findings from academia to applications.
5. Education and outreach activities will be performed at the graduate, undergraduate, and K-12 levels. A multidisciplinary training program will be established at the graduate and undergraduate level. Agile marine autonomy will be taught in a robotics course, and a new textbook on will be developed.

WORK COMPLETED

We have developed generic environmental modeling in two applications using different types of AUVs. We have used a YSI Ecomapper for bathymetry survey, where the GEM is built to represent the bathymetry data. We have also used underwater gliders for ocean sampling, where the GEM is built to represent ocean flow.

The EcoMapper (Figure 1, upper right) is an autonomous underwater vehicle purchased from YSI Inc. It is operated through “Windows remote desktop” via Wi-fi. GPS is available for localization on water surface and DVL (Doppler Velocity Log) is employed for localization underwater relative to the bottom. Our Ecomapper is also equipped with Conductivity and Temperature Sensors, Depth Sensor (measure depth from surface), Depth-Sounding sonar (measures height from bottom) and Three-axis digital compass. If operating in the autonomous mode, the EcoMapper follows a predefined course, either on surface or below surface and records all sensor measurements into log files. As part of an NSF funded project “Autonomous Control and Sensing Algorithms for Surveying the Impacts of Oil Spills on Coastal Environments” led by the PI, the EcoMapper was deployed to survey the tidal lagoon located at the Grand Isle State Park (Figure 1, upper left) in Louisiana where oil pollutions have been spotted in 2010. Five autonomous missions between surface and 0.5 meters below surface were executed. By interpolating the DVL data, we obtained a bathymetry map for this pond (Figure 1, bottom). The salinity of the lagoon varies between 13ppt and 17ppt under different weather condition.

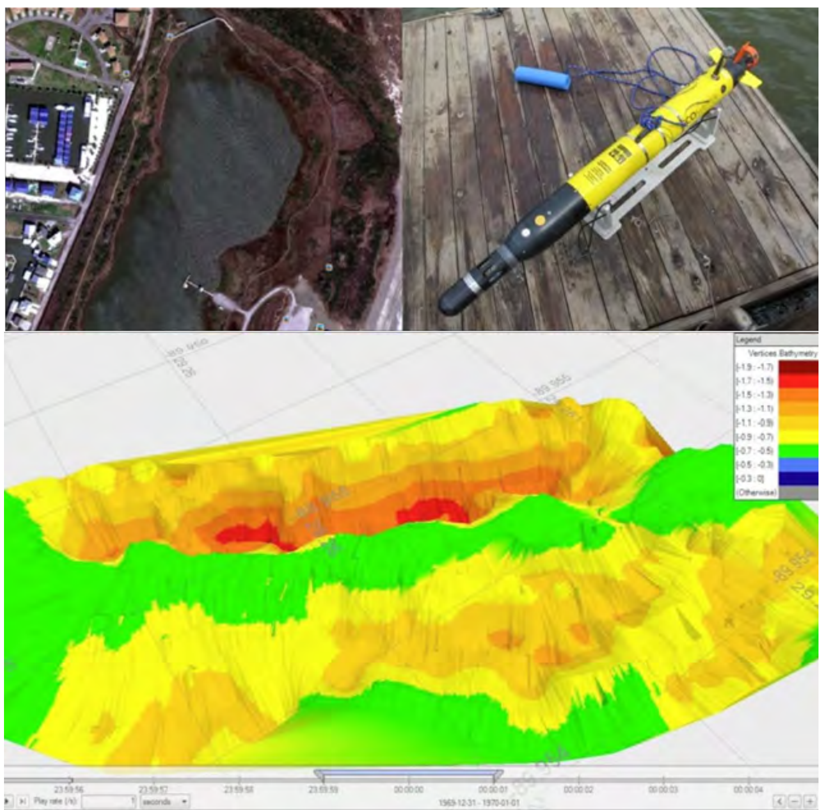

Figure 1. Bathymetry survey using an YSI Ecomapper for a retention pond in Grand Isle State Park, LA

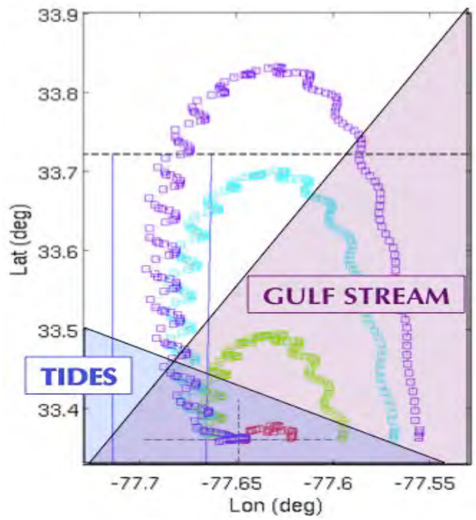

Figure 2. A station-keeping algorithm produces paths of simulated gliders in Long Bay, SC. A GEM is developed to combine tides and the gulfstream.

Two Slocum underwater gliders will be deployed in Long Bay, SC for an NSF project:

"Mechanisms of nutrient input at the shelf margin supporting persistent winter phytoplankton blooms downstream of the Charleston Bump." PI's team will control the motion of the two gliders to navigate near the edge of the Gulfstream, where strong current exceeding glider horizontal speed is often observed. We developed a GEM combining a simple tidal and Gulfstream current model based on M2 tide and sinusoidal meandering motion of Gulf Stream as shown in Figure 2. HYCOM (HYbrid Coordinate Ocean Model, http://www.hycom.org) will later be integrated into the GEM. Using the Glider Coordinated Control Systems (GCCS) developed by PI's team, we simulate a control algorithm to maintain a glider's position near the edge of Gulfstream. Starting from different positions, the trajectories for station holding are illustrated in Figure 3. It can be observed that the glider is able to escape from a strong northward Gulfstream current and come back to its desired position at the cross hair near the bottom of the figure.

A dynamic programming approach has been implemented to generate optimal paths for an underwater glider to maintain minimal distance from a set goal point under the influence of flow. This approach uses a cost function that integrates the glider's distance from the goal over a finite time horizon. The domain of operation is discretized in both space and time, and the cost-to-go and associated optimal control actions are computed at each point in the discretized domain, starting at the final time (see Figure 4). The glider's position is then integrated forward using a simple particle model for the glider dynamics. At each time step in the integration, the glider's control action (e.g. the choice of heading angle) is taken to be a bilinear interpolation of the optimal control actions at the nearest states in the discretized domain. The glider's total velocity is taken as a sum of the glider's through-water velocity and the predicted flow velocity, which is obtained from the GEM used. This gives a near-optimal trajectory that can be converted to a waypoint list to be passed to the glider.

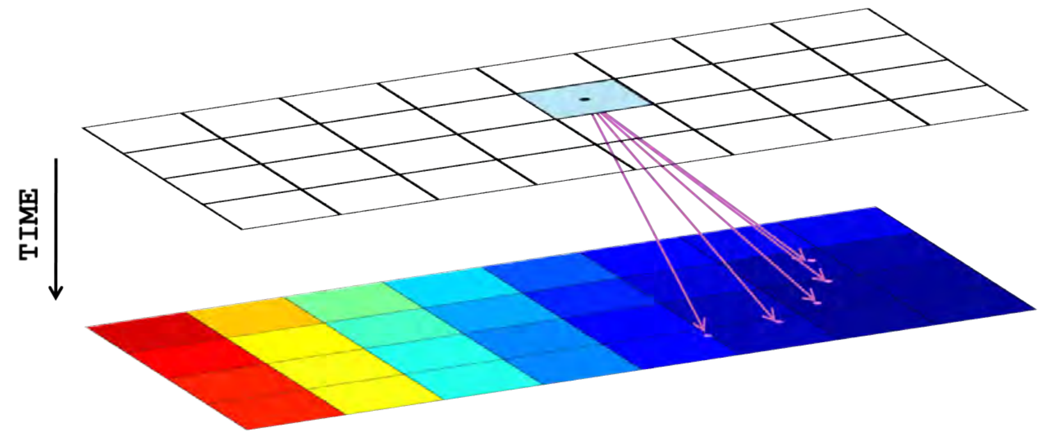

Figure 3. An illustration of dynamic programming for glider path planning. The arrows represent possible motions of the glider over one time step, given different available control actions (heading angles); the glider's final position at the next time step depends on both the heading angle and the ambient flow. The value function at the current state (blue rectangle in the top layer) is given by the minimum over all possible heading. angles of the sum of the current distance from the goal and the value function at the glider's final position.

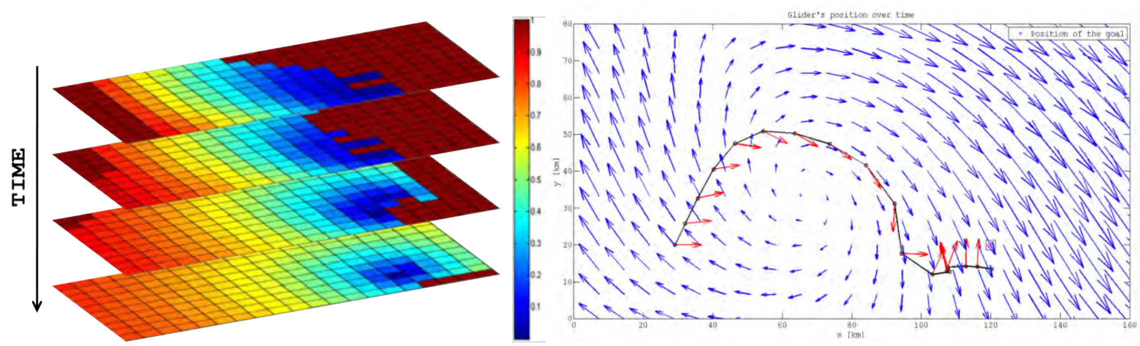

Figure 4. Dynamic programming-based path planning over a sample domain with a static flow field. The value function for all x,y positions is shown at selected time slices (left). The red on the far left and right sides of the domain marks the infeasible positions from which the glider will be carried out of the domain by the flow within the planning time horizon regardless of the control action taken (the cost at these positions is maximized). Given the value function, a path to the goal can be computed from an arbitrary starting position (if it is feasible). A sample path is shown in the figure on the right. The blue arrows show the flow velocity over the domain. The red arrows show glider headings along the path. The goal position is marked by an asterisk.

The dynamic programming path-planning algorithm has been tested in the simulation module of GCCS, which uses ocean-model flow data and an approximated model of glider dynamics, as well as an implementation of the glider's on-board control algorithms, to simulate glider motion given waypoint lists passed to the glider. Figure 4 shows a planned path in a simulated flow field.

RESULTS

We use controlled Lagrangian particle tracking (CLPT) to evaluate the accuracy of the simulated glider position. Errors in glider position simulation are due to limited resolution of ocean models, missing physics in the models, and sparseness of available ocean measurements used to drive the model. Using a modified Langevin equation to model the growth of the expected glider position error (termed CLPT error), we have shown that the magnitude of the expected error in simulated position grows exponentially until reaching a lower bound equal to twice the grid size of the ocean model used (see Figure 5). The error growth then slows to a polynomial function of time.

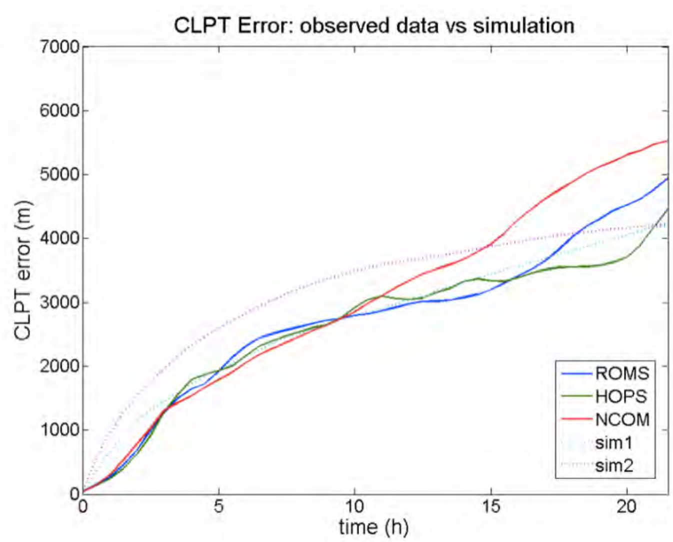

Figure 5. CLPT error growth over time. This data was collected during the 2006 ASAP experiment in Monterey Bay, CA. The simulated glider positions were computed using 3 ocean models (Regional Ocean Modeling System (ROMS), Harvard Ocean Prediction System (HOPS), and Navy Coastal Ocean Model (NCOM)). True glider positions were obtained from GPS fixes from the gliders over the course of the experiment. The plots show average error for all gliders and all days of the experiment for which data is available. The dotted lines show the expected value of the CLTP error over time, based on our Langevin model of CLPT error growth. Agreement between the model and the data suggests that the Langevin equation-based approach can be used to evaluate the accuracy of GCCS position simulation in future glider deployments.

IMPACT/APPLICATIONS

Technology advancement has been a driving force for changes in Naval battle strategies. The Pearl Harbor attack marked the diminishing of surface-surface warfares between gunships and the beginning of the era of Naval airforce. The Falklands Naval War between Agentina and the UK demonstrated the

devastating power of guided air-surface missiles. The Navy and other branches of the armed forces are now in transition to a new era of unmanned systems. The next Naval battle may prove that an agile marine autonomy is key to victory. The GEMs proposed in this proposal are stepping stones for unmanned marine systems to react promptly to a changing operational environment so that they can gain an upper hand by out-maneuvering their opponents. The generic nature of the methods makes GEMs scalable and portable. Furthermore, as the intelligence of unmanned systems grows, GEMs may be shifted from the network level to the platform level to achieve a new level of agile autonomy.

RELATED PROJECTS

Generic environment modeling and agile autonomy are closed connected with other ONR and NSF projects the PI is participating.

1. ONR: Automation Middleware and Algorithms for Robotic Underwater Sensor Networks. PI has just finished this three-year project where we have created the theory of controlled Lagrangian Particle Tracking (CLPT) and extended the functionality of the Glider Coordinated Control System (GCCS). Both the CLPT and GCCS will be further developed in the current project.
2. ONR: Bio-Inspired Autonomous Control for Optimal Exploration and Exploitation in Marine Environments (BioEx). PI participated in this project. The project goal is to institute an innovative multidisciplinary investigation of autonomous collective foraging in a complex environment that explicitly integrates models and insights from biology with models and provable strategies from control theory. The work on Agile autonomy is complementary to the bio-inspired engineering solutions on autonomy.
3. NSF: Mechanisms of Nutrient Input at the Shelf Margin Supporting Persistent Winter Phytoplankton Blooms Downstream of the Charleston Bump. We will deploy underwater gliders in Long Bay, SC to study mechanisms of nutrient input at the shelf margin supporting persistent winter phytoplankton blooms downstream of the Charleston Bump. GEM and GCCS has been applied to this project.

PUBLICATIONS

Journal articles:

W. Wu and F. Zhang, "Cooperative Exploration of Level Surfaces of Three Dimensional Scalar Fields," *Automatica, the IFAC Journal* 47(9): 2044-2051, 2011. [published, refereed]

K. Szwaykowska and F. Zhang, "Trend and Bounds for Error Growth in Controlled Lagrangian Particle Tracking," *IEEE Journal of Oceanic Engineering*, 2011. [submitted, refereed]

Refereed Conference Proceedings:

K. Szwaykowska and F. Zhang, "A Lower Bound for Controlled Lagrangian Particle Tracking Error, " in *Proc.49th IEEE Conference on Decision and Control (CDC 2010)*, 4353-4358, 2010. [published, refereed]

K. Szwaykowska and F. Zhang, "A Lower Bound on Navigation Error for Marine Robots Guided by Ocean Circulation Models ," in *Proc. 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2011).* [published, refereed]

HONORS/AWARDS/PRIZES

Recipient: Fumin Zhang
Institution: Georgia Institute of Technology
Award: 2010 ONR YIP Award
Sponsor: Office of Naval Research

Recipient: Fumin Zhang
Institution: Georgia Institute of Technology
Award: 2010 Lockheed Inspirational Young Faculty Award
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Recipient: Fumin Zhang
Institution: Georgia Institute of Technology
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Award: Distinguished Lecturer on Cyber-Systems and Control
Sponsor: Zhejiang University, China

Recipient: Georgia Tech Savannah Robotics (Supervised by Fumin Zhang)
Institution: Georgia Institute of Technology
Award: 2011 Martin Klein MATE Mariner Award
Sponsor: Marine Advanced Technology Education (MATE) Center